Supernova Asymmetries

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Abstract.
All core collapse supernovae are strongly aspherical. The "Bochum event," with velocity components displaced symmetrically about the principal Hα line, strongly suggests that SN 1987A was a bi-polar rather than a uni-polar explosion. While there is a general tendency to display a single prominant axis in images and spectropolarimetry, there is also growing evidence for frequent departures from axisymmetry. There are various mechanisms that might contribute to large scale departures from spherical symmetry: jet-induced processes, the spherical shock accretion instability (SASI) and associated phenomena, and non-axisymmetric instabilities (NAXI). The MRI gives inevitable production of large toroidal magnetic fields. In sum: no Ω without B. The role of magnetic fields, non-axisymmetric instabilities, and of the de-leptonization phase are discussed.

INTRODUCTION

All core collapse events with adequate spectropolarimetric observations have proven to be polarized and hence to depart from spherical symmetry in some substantial way (Wang et al. 2001, 2003; Leonard et al. 2001a,b, 2006). Much of the spectropolarimetry shows a tendency for the data to be distributed along a single locus in the plane defined by the Stokes parameters Q and U. We are coming to understand, however, that departures from a single locus are rather common, and possibly systematic. This implies a breakdown in axisymmetry that must be understood. Although this is becoming generally recognized with recent detailed spectropolarimetric studies of distant supernovae, SN 1987A provided the first evidence (Cropper et al. 1988; Jeffery 1991).

On the theoretical side, core collapse generically produces a structure in the proto-neutron star that has a strongly negative angular velocity gradient and hence is unstable to the magnetorotational instability (Velikov 1959; Chandrasekhar 1960; Acheson & Gibson 1978; Balbus & Hawley 1991, 1998). The MRI will exponentially grow the magnetic field on the rotational timescale by a self-induced turbulent dynamo process and produce strong, primarily toroidal magnetic fields in the proto-neutron star (Akiyama et al. 2003). It is not truely self-consistent to consider rotating core collapse without the concomitant growth, saturation, and subsequent evolution of this magnetic field. The ultimate problem is complex, involving rotation, magnetic fields, and neutrino transport, but it involves very interesting, and still underexplored, physics.
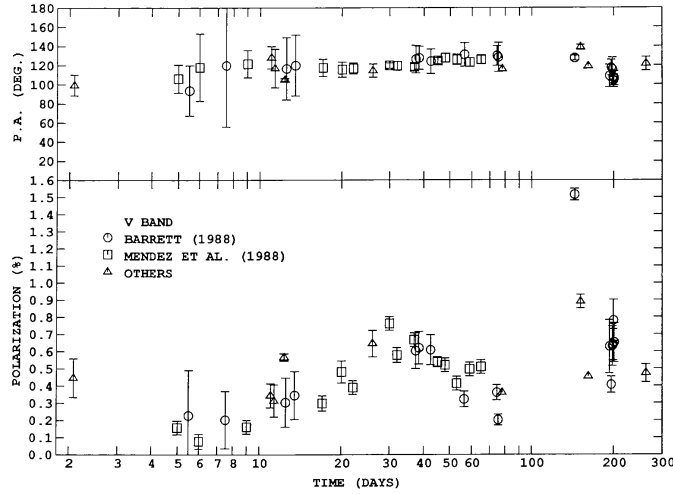
FIGURE 1. Evolution of the V-band polarization, and associated polarization angle, of SN 1987A from Jeffery (1991).

SPECTROPOLARIMETRY

The first supernova for which good photometric and spectropolarimetric data were obtained was SN 1987A. This data has still not been adequately explored and we can view it now in the context of the growing data base of more distant, but ever better studied supernovae. Jeffery (1991) summarized the photometric polarimetry obtained on SN 1987A (Fig. 1). Both B band and V band data showed a slow growth to a polarization of 0.4 - 0.7% by day 30 - 40. The polarization then declined to a value near 0.2 - 0.3% by day 100. Around day 110, when the major maximum gave way to the exponential radioactive tail, the polarization jumped to 1.3 to 1.5% and then slowly dropped back to around 0.2 to 0.4% by day 200. This jump is clearly associated with the photosphere receding through the outer hydrogen envelope and revealing the inner core. This behavior was caught again for the Type IIP SN 2005dj by Leonard et al. (2006). SN 1987A gave clear evidence that the inner machine of the explosion was strongly asymmetric, evidence that has proven ubiquitous with current, systematic observations. Another remarkable fact is that the polarization angle did not waver through this whole evolution, including the large spike in polarization. SN 1987A "pointed" in a certain direction and maintained that orientation througout its development (Wang et al. 2002). This cannot be due to Rayleigh-Tayler nor Richtmyer-Meshkov instability. Other, large scale, systematic, directed asymmetries must be at work. The "Bochum event," with velocity components displaced symmetrically about the principle Hα line, strongly suggests that SN 1987A was a bi-polar explosion (Hanuschik et al. 1989; Wang et al. 2002).

   On the other hand, the excellent spectropolarimetry of Cropper et al. (1988; Fig. 2) showed that as data is tracked as a function of wavelength over spectral features, the polarization angle does sometimes change with wavelength, giving rise to "loops" in the plane of the Stokes parameters, Q and U. This means that there must be some substantial
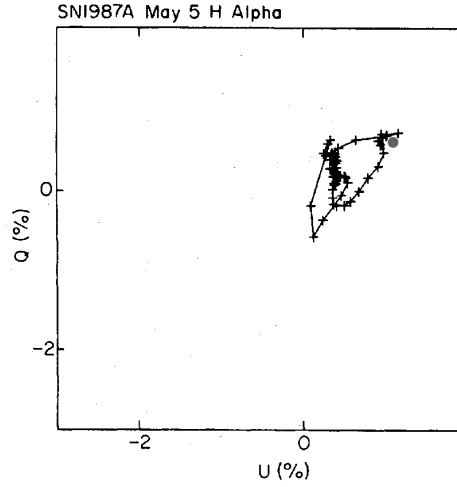
FIGURE 2. Hα, on the $Q - U$ plane, of SN 1987A on May 5 1987 from Cropper et al. (1988). The filled grey circle is the ISP, effectively the origin of polarization intrinsic to SN 1987A, on the $Q - U$ plane from Mendez (private communication).

departure from axisymmetry imposed on the overall "pointed" behavior revealed by the photometric polarimetry. The loops are a locus with respect to wavelength, which itself is a probe of velocity slices in the homologously expanding matter. This polarimetric behavior thus gives a rich phenomenology that is ripe in SN 1987A and other events for progress in physical understanding. These loops will give greater insight into the composition-dependent three-dimensional structure of the ejecta.

Two other examples of non-axisymmetric loop structures in polarization data are given in Maund et al. (2007a, b). Maund et al. (2007a) discuss data on the Type IIb event SN 2001ig. Four days after discovery, when the supernova was still in the H-rich phase, the blended Hα/He I 6678 P-Cygni feature shows a distinct loop in the Q/U plane, again signifying a systematic departure from axisymmetry (Fig. 3; left panel). In this case, the blending of the two lines plays a special role. Maund et al. (2007b) present data on the weird Type Ib/c SN 2005bf that resembled a helium-poor Type Ic in early data, but developed distinct helium-rich Type Ib features later (Wang & Baade 2005; Folatelli et al. 2006). Our observations on May 1, 2005, 34 days after the explosion, 18 days after the first peak in the light curve, and 6 days before the second peak, show a distinct loop in the He I 5876 line (Fig. 3; right panel). Related complex structures were revealed by the high-velocity Type Ic SN 2002ap (Wang et al. 2003). Thus although the sample is still small, evidence for non-axisymmetry may be ubiquitous.

A full understanding of the spectropolarimetry requires allowance for the background polarization of the interstellar medium of our Galaxy, the host galaxy and, perhaps, the circumstellar environment of the supernova. Cropper et al. (1988) presented their data with no reference to this background. Jeffery (1991) quotes Mendez (private communication) as determining the ISP to be about Q = +0.36% and U = +0.89%. This component "stayed constant for about 6 months and seemed Serkowski-like." Care must be taken since any ground-based point-spread function would include data from all the background stars, some of which are Be stars that could be intrinsically, and variably
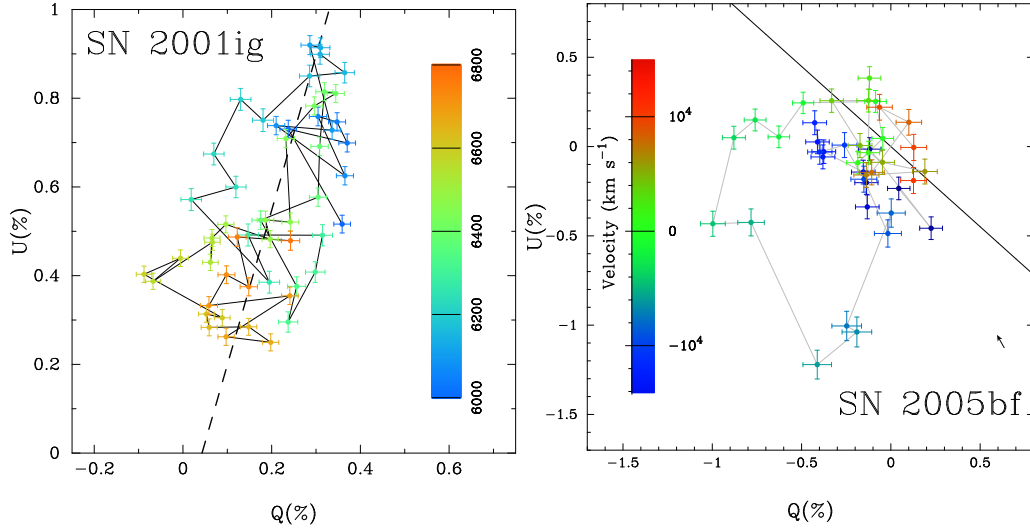
FIGURE 3. $Q-U$ plane loops, corrected for the relevant ISP, of He I 6678Å/Hα in the Type IIb SN 2001ig and He I 5876Å in the Type Ib/c SN 2005bf (Maund et al. 2007a; Maund et al. 2007b).

polarized themselves, a problem for all extragalactic data. Taking the Mendez results at face value gives a somewhat different perspective on the Cropper et al. data. For instance, as originally plotted, the Cropper et al. data give the impression that on June 3, after the transition to the radioactive tail and during the spike of maximum photometric polarization, the Hα and Ca II IR features appear to show large "loops" that are co-aligned, but in some sense mirror images of one another with Hα extending to positive Q and U and Ca II extending to negative Q and U. With the Mendez ISP point (Fig. 2), the June 3 Hα loop is roughly symmetric in its major extent around the ISP point, but Ca II only extends to negative values. Both "loops" appear to have a net displacement to the positive Q side of a line parallel to the major axis of the loop and passing through the ISP point. The similarities and differences between these polarization structures are worth study in considerable more depth.

Departure from axisymmetry and specifically the formation of "loops" has been discussed by Kasen et al. (2003) in the context of Type Ia supernovae and by Hoffman (2007) in the context of Type IIn supernovae. These structures could be caused by clumps of high-opacity material partially obscuring a polarized photosphere or by coherent, non-axisymmetric, composition-dependent, structures in the ejecta.

Core collapse supernove, including SN 1987A, thus show strong evidence for axisymmetry, but also significant departures from axisymmetry. The issue thus arises as to what physical processes drive the breakdown in spherical symmetry.

THE PHYSICS OF ASYMMETRY

Spherical Accretion Shock Instability: SASI

Blondin, Mezzacappa & DeMarino (2003) showed that the standing shock that forms after core collapse will be unstable. There is still controversy as to whether this is a purely acoustically-driven instability that propagates primarily azimuthally (Blondin & Mezzacappa 2006) or whether there is some radially-coupled vortical/acoustic feedback loop (Foglizzo et al. 2007). Burrows et al. (2006) have argued that the SASI may lead to, but be different from, a large scale instability in which g-modes are excited on the proto-neutron star surface that drive a large acoustic flux that could play a role in the explosion, perhaps making a substantially axisymmetric, but uni-polar explosion. As remarked above, SN 1987A, at least, appears to have been truely bi-polar. There is, in any case, no doubt that the basic SASI instability exists. It must be taken into account in the physics of core collapse, and it will tend to introduce substantial asymmetries.

Most of the simulations to date are 2D, non-rotating, and have no magnetic fields. Some omit neutrino transport. An important step was taken by Blondin & Mezzacappa (2007) to investigate the SASI in 3D. Remarkably, they found that a model with an initially non-rotating iron core, and hence no net angular momentum, produced a proto-neutron star rotating at with a 50 msec period. This comes about because the SASI in 3D produces substantial lateral flows in the outer portions. To maintain conservation of angular momentum, an equivalent, but oppositely directed, angular momentum must be accreted onto the core. Young & Fryer (2007) find a similar behavior in 3D SPH calculations. This sort of behavior is extremely interesting since it relaxes the coupling between the rotational state of the original iron core and the spin rate of the neutron star that subsequently forms (see also Akiyama & Wheeler 2005).

Non-Axisymmetric Instabilities (NAXI) in the Neutron Star

Rotation with ratio of rotational to binding energy $T/|W| > 0.01$ ($P \sim 20$ - 30 msec) may be subject to non-axisymmetric instability (Andersson 1998; Shibata et al. 2003; Ott et al. 2005). The thresholds, growth rates, and saturation, depend on the degree of differential rotation (Tohline & Hachisu 1990; Rampp et al. 1998; Centrella et al. 2001; Imamura & Durisen 2004; Ou et al. 2004) and will be affected by magnetic fields (Rezzolla, Lamb & Shapiro 2000, 2001a,b). A dynamic instability to a bar-like mode can occur for $T/|W|$ as low as ~ 0.2. The criterion $T/|W| > 0.27$ is neither necessary nor sufficient for dynamical instability (Shibata & Sekiguchi 2005).

Most work on non-axisymmetric instabilities considers the neutron star to be in complete isolation and ignores the magnetic field; both are potentially significant. In the current context, it is important to realize that for sufficiently rapidly rotating proto-neutron stars, these NAXI can occur deep inside the supernova material, before it has time to expand and dissipate. The MRI will grow magnetic field faster than all but dynamical bar-modes. This means that the non-axisymmetric instabilities will usually occur in a magnetized medium.

Ou & Tohline (2006) examined the NAXI due to the presence of a co-rotation point within a "resonant cavity" formed by an extremum in vorticity density in a differentially rotating structure that serves to reflect acoustic waves. Note that while one-armed m = 1 spiral modes can be generated by this mechanism and by the SASI, the azimuthal acoustic modes due to the SASI are not the same as those of the NAXI in a differentially-rotating proto-neutron star.

It is important to note that the density distribution near the region of peak shear and magnetic field in a proto-neutron star (the boundary of the homologous core) is approximately independent of whether a supernova has been successful or not in the interval 100 msec to 1 s after bounce. This means that the NAXI will interact with surrounding, magnetized matter. The result is likely to be the generation of significant magnetoacoustic flux that will propagate out into the ambient matter, whether or not an explosion has been initiated by some other mechanism (Wheeler & Akiyama 2007). Note also that according to the results of Blondin & Mezzacappa (2007) and of Young & Fryer (2007), non-rotating iron cores can potentially generate rotating neutron stars subject to NAXI, and hence to magnetoacoustic flux. Wheeler & Akiyama (2007) estimate that for parameters appropriate to the proto-neutron star, a luminosity $L_{mhd} \sim 10^{50-52}$ erg s^{-1} could be radiated in magnetoacoustic flux on a time scale somewhat shorter than the de-leptonization time. At the larger end of this range, corresponding to T/|W| near the upper limit of 0.14, the luminosity is quite competitive with neutrino heating rates.

The De-leptonization Phase

The proto-neutron star formed at core bounce will radiate binding energy in neutrinos, contract, and spin up. The time for de-leptonization is ~ 10 s to radiate most of the neutrino energy. The time is shorter for the contraction of the radius, the key factor in spinning up the neutron star. The former is comparable to the time for the blast wave to propagate out of the C/O or He core. This means that de-leptonization also does not occur in the vacuum of space, but takes place within the matter-filled environment in the center of the supernova, whether it is in the process of exploding or not.

The tendency for the de-leptonizing PNS to spin up will render it broadly susceptible to non-axisymmetric instabilities, the production of magnetoacoustic luminosity, and dissipation of rotation. The evolution depends on the strength of that dissipation, but in general the time for dissipation of the rotational energy by magnetoacoustic flux will be less than the time for de-leptonization, ~ 10 s. Constraints on the energetics of the de-leptonization phase are given by Wheeler & Akiyama (2007).

Jet-Induced Models

The tendency for core collapse supernovae to follow a fixed axis has motivated interest in jet-induced explosions (Khokhlov et al. 1999). Rotation and magnetic fields are important ingredients in core collapse and those factors commonly lead to jets in many

astrophysical environments. It still remains a significant challenge to understand how rotation and concomitant magnetic fields will lead to jets in the context of core collapse.

Many groups are beginning to do rotating, magnetic simulations, but it is very challenging numerically to achieve the kind of numerical resolution needed to resolve the MRI (Obergaulinger et al. 2006 and references therein). Given that practical limitation, many groups have elected to do simulations with exaggerated initial magnetic fields and/or fields with exaggerated poloidal structure. Poloidal fields coupled with shear will naturally amplify the field strength by field-line wrapping. This is a generically slow process since it depends linearly on the winding. To get "useful" results it is necessary to have the poloidal configuration be significantly strong. Neither a weak poloidal configuration nor a strong toroidal initial configuration are likely to produce interesting jet-like behavior in the absence of a numerical capability to follow the growth of the non-axisymmetric MRI that can and will grow from a modest initial toroidal magnetic field. Calculations assuming an initially strong poloidal field can produce spectacular numerical results (for a recent example, see Burrows et al. 2007), but it is not clear that these simulations reflect what Nature is doing. The initial field is likely to be modest and substantially toroidal, not poloidal, since it is likely to have been generated by shear in the progenitor star. The same is true, of course, for the field generated by the MRI or other dynamo processes in the proto-neutron star. The challenge is to understand whether and how a jet is formed from an initially modest toroidal magnetic field. Note again that the initial iron core rotation might be modest. If SASI-like processes spin up the neutron star independent of the initial core rotation and the rotation is enhanced during de-leptonization, there is still plenty of time and opportunity to affect the explosion dynamics with MHD jet and magnetoacoustic phenomena.

CONCLUSIONS

Core collapse supernovae, including SN 1987A, show departures from both spherical and axial symmetry. There is substantial evidence that the explosion of SN 1987A itself was truly bi-polar, but with important and interesting departures from axisymmetry. The proto-neutron star that forms after core collapse will be rotating and will have a concomitantly strong, predominantly toroidal magnetic field. These conditions might form a jet, but they are also conditions that could give rise to a strong, magnetoacoustic wave-generating engine. Supernovae make a loud noise!

The role of non-axisymmetric instabilities may help to explain the spectropolarimetry of core collapse supernovae and may also have major implications for supernova physics as well as for pulsar magnetic fields and spins.

ACKNOWLEDGMENTS

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